RHEMEDiation

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RESTORE OUR OCEAN & WATERS

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## REDUCING CHEMICAL POLLUTION THROUGH

# INNOVATIVE NATURE-BASED WATER TREATMENT

## RHE-MEDiation

**Funded by the European Union's Horizon Europe program, RHE-MEDiation[1] is a three-year project (2023-2026) coordinated by RINA Consulting SpA that aims to destress the Mediterranean Sea from chemical pollution, by testing and validating an innovative remediation technology: microalgae-based photobioreactors. These photobioreactors were integrated within existing water/wastewater treatment systems to enhance the removal of nutrients, heavy metals and forever chemicals. The system also includes mobile and fixed sensing systems to identify and measure chemical substances in fresh, sewage and marine waters. The data from these sensors are uploaded to the European Marine Observation and Data Network (EMODnet) data portal to contribute to the Digital Twin of the Ocean.**

This document presents the main policy-relevant outcomes from the RHE-MEDiation project.

## RHE-MEDiation partner organisations

The RHE-MEDiation consortium consists of 11 partners representing large enterprises, academia, research organisations, SMEs, water and wastewater management companies, and the European Marine Board.

## Destressing the Mediterranean Sea from chemical pollution

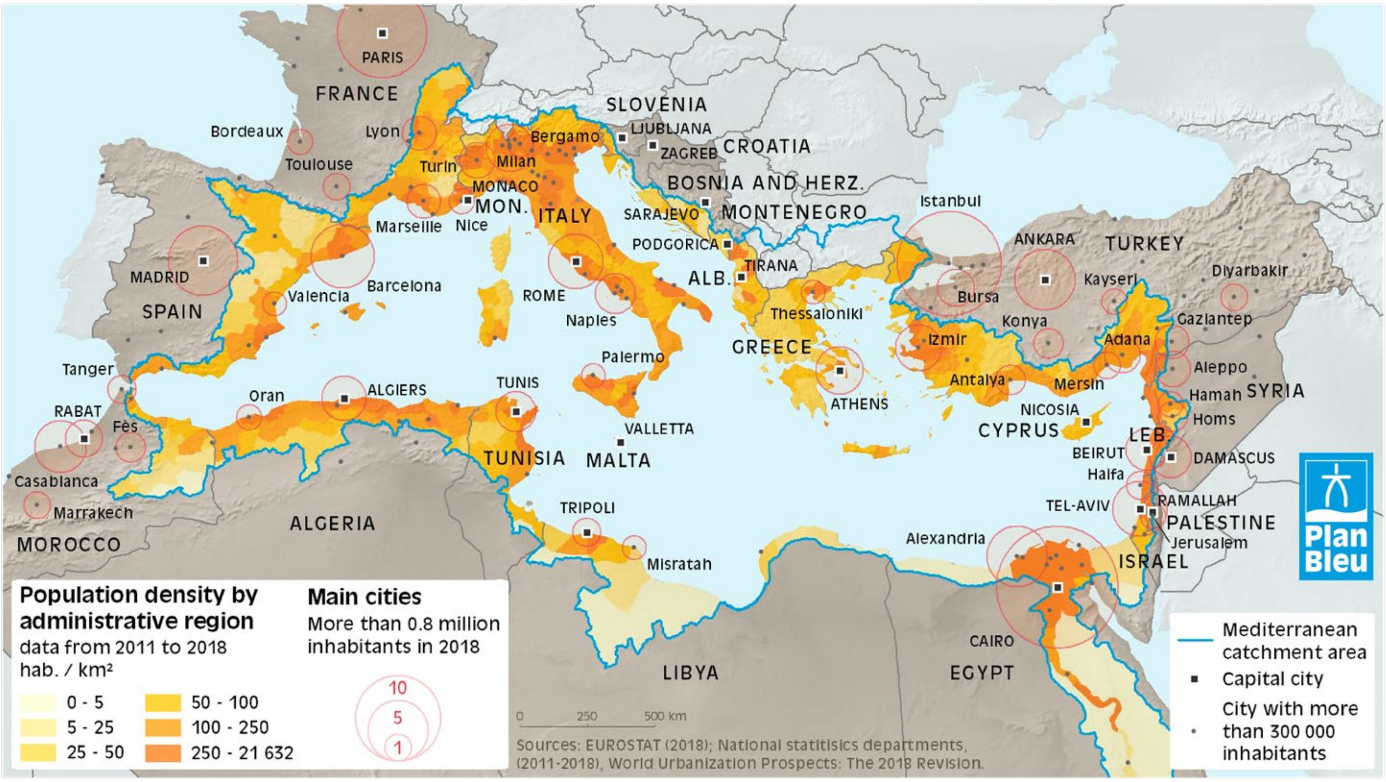
The Mediterranean Sea is a semi-enclosed basin (Figure 1), with approximately 250 million coastal inhabitants, and hosts a third of the world's tourists annually (360 million in 2024[2]). This region also experiences high levels of agricultural and industrial activities, and intense maritime traffic. Its unique geography and oceanography traps pollutants, which along with its high population density, heavy industry, and sometimes inefficient waste management, result in **significant marine pollution**. Pollutants come from land-based sources, via discharge points and dumping grounds, from surface fluvial run-off, and through atmospheric deposition. Other pollutants are derived directly from marine activities such as shipping, mining, and oil and gas exploration (UNEP/MAP and Plan Bleu, 2020).

To prevent and eliminate pollution in the Mediterranean Sea, the European Union (EU) launched the "Mediterranean Lighthouse" under the **EU Mission to "Restore our Ocean and Waters by 2030"**[3]. The Mission Ocean "Lighthouses" pilot, demonstrate, develop and deploy activities across EU seas and river basins to support implementation, regional engagement and cooperation. The RHE-MEDiation project supports the "Mediterranean Lighthouse" in preventing, minimising and controlling pollution, as well as eliminating and remediating existing pollution hotspots in the Mediterranean.

1 https://rhemediation.eu/

2 IUCN, IATUR, IDDRI & eco-union. (2025). Sustainable Blue Tourism in the Mediterranean: Trends, Challenges, and Policy Pathways. Blue Tourism Initiative. IUCN Centre for Mediterranean Cooperation, Málaga, Spain. https://bluetourisminitiative.org/main-publications/sustainable-blue-tourism-in-the-mediterranean-trends-challenges-and-policy-pathways/

3 https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters_en




Credit: UNEP/MAP and Plan Bleu, 2020

**Figure 1:** Population density by administrative region and main cities in the Mediterranean catchment area. (Source: EUROSTAT, 2018; National statistics departments, 2011-2018; UNDESA, World Urbanization Prospects: The 2018 Revision).

Under **the Barcelona Convention**[4], the EU and the other contracting parties pledged to take appropriate measures to prevent, abate, combat and eliminate pollution to the fullest extent in the Mediterranean Sea. Its Protocol for the Protection of the Mediterranean Sea Against Pollution from Land-Based Sources and Activities translates these commitments into specific objectives to reduce and phase out substances that are toxic, persistent and liable to bioaccumulate, such as Persistent Organic Pollutants (POPs), marine litter and mercury.

In the EU, these objectives are implemented through a set of binding regulatory instruments, designed to reduce pollution in marine and freshwater ecosystems. **The Water Framework Directive (WFD)**[5] highlights actions required to prevent eutrophication caused by nutrients, to eliminate and/or minimise the impact of micropollutants and forever chemicals, and to maintain good ecological and chemical status in European waters. The **Marine Strategy Framework Directive (MSFD)**[6] provides thresholds and assessment criteria to monitor the marine environment, including those to ensure that heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and pesticides do not impact the Good Environmental Status (GES) of European marine waters. The 2025 **European Water Resilience Strategy** outlines actions to achieve three key objectives to restore and protect the water cycle, from source to sea:

1) build a water-smart economy to boost competitiveness,
2) attract investment and promote the EU's water industry, and
3) secure clean and affordable water and sanitation for all.

In parallel, the EU promotes a circular approach to water and waste treatment: the **Water Reuse Regulation**[7] incentivises the use of reclaimed water in crop irrigation and in relevant industrial activities, while reducing the application of synthetic fertilisers and demand for fresh water. The revised **Urban Wastewater Treatment Directive (UWWTD)**[8] enhances requirements for monitoring, reporting and pollution reduction at source. It requires tertiary treatment[9] for nutrient removal to avoid eutrophication, and reduction of micropollutants with quaternary treatment. It also requires treatment plants to collect and treat wastewater in all urban areas with more than 1,000 inhabitants by 2035 and be energy-neutral and reduce their greenhouse gas emissions by 2045. It also encourages the reuse of treated water in water-stressed regions such as the Mediterranean.

4 https://www.unep.org/unepmap/who-we-are/barcelona-convention-and-protocols
5 Directive 2000/60/EC https://eur-lex.europa.eu/eli/dir/2000/60
6 Directive 2008/56/EC https://eur-lex.europa.eu/eli/dir/2008/56
7 Regulation (EU) 2020/741 https://eur-lex.europa.eu/eli/reg/2020/741
8 Directive 2024/3019 https://eur-lex.europa.eu/eli/dir/2024/3019
9 Process following secondary treatment, aimed at removing pollutants not adequately removed by previous treatments (e.g. trace organics, suspended solids, dissolved solids, metals).

These policies and regulations set **many requirements for water treatment. In addition, periodic upgrades are needed to enable tailored and long-term solutions,** particularly to be compliant with the revised UWWTD stricter requirements. This is especially relevant considering that approximately 80% of assessed European marine ecosystems were found to be disturbed by contaminants (EEA, 2019).

The **challenge of managing water pollution in the Mediterranean Sea** does not stem from the lack of scientific knowledge or policy frameworks, but from **uneven implementation and enforcement,** compounded by **wide disparities in economic capacity among Mediterranean countries** (Ziveri et al., 2023). Despite existing policy commitments, 21% of wastewater in the region only undergoes basic treatment, and less than 8% undergoes tertiary treatment (UNEP/MAP and Plan Bleu, 2020). In addition, while the UWWTD establishes an overall policy objective of achieving 80% of pollutant removal for substances such as per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, microplastics and chemicals in personal care products, its regulatory framework lacks compound-specific, enforceable targets for many of these highly diverse chemical compounds (e.g. there are approximately 10,000 different PFAS compounds).

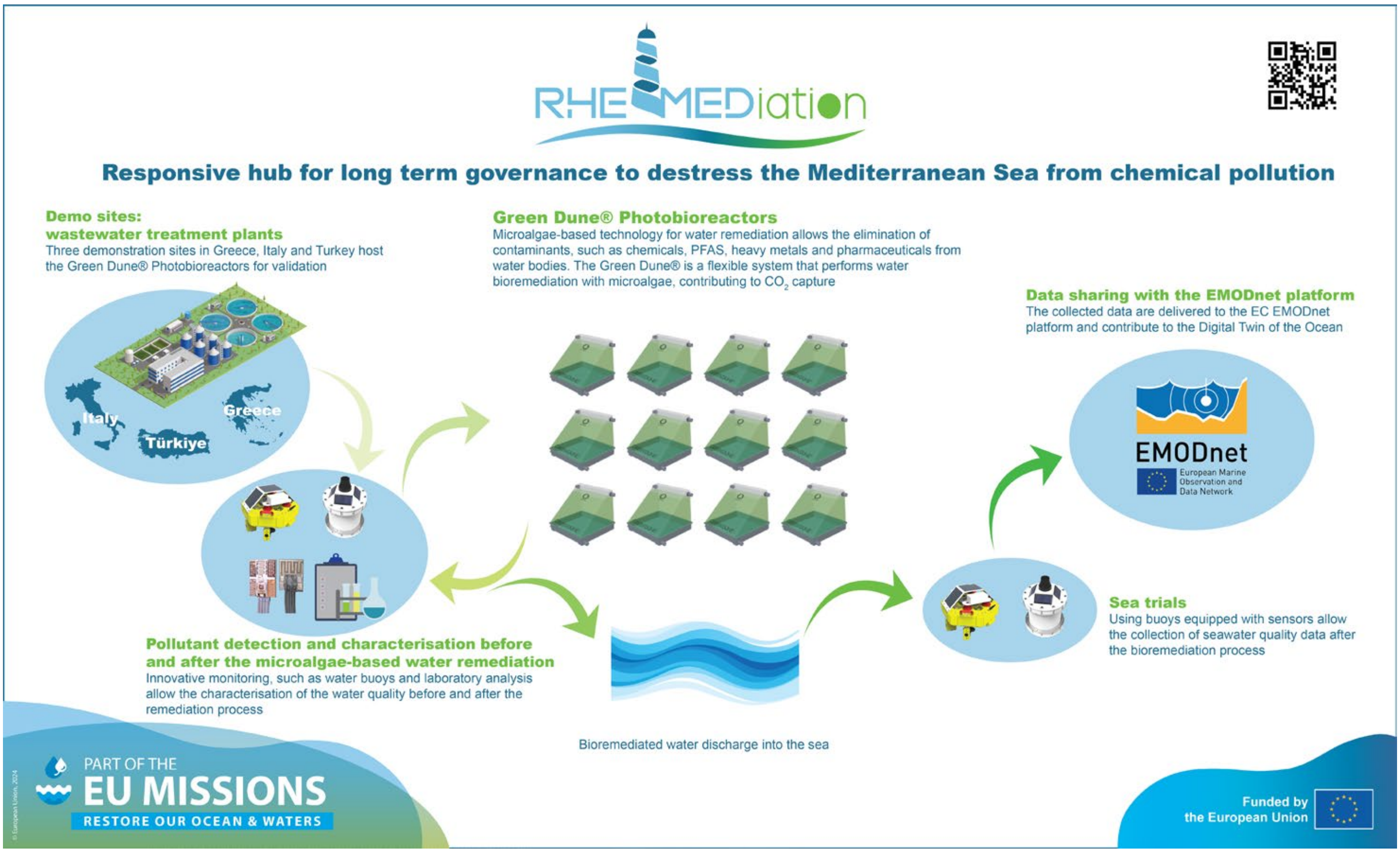
Although wastewater treatment plants are increasing their ability to treat or eliminate certain substances, there will probably never be suitable technological or financial resources to remove 100% of waterborne pollution. Therefore, **pollution prevention must be a priority.** These should include the reduction and phasing-out of known harmful substances at source, mandatory and strongly enforced environmental and social (including health) impact assessments for new substances, and being prepared and responsive for accidental pollution (UNEP/MAP and Plan Bleu, 2020).

## The RHE-MEDiation approach

Many wastewater treatment plants are not yet able to achieve the increasing pollution reduction targets, and **the EU wastewater and water protection frameworks do not yet recognise and incentivize the deployment of innovative and nature-based treatment technologies such as microalgae-based photobioreactors.** These photobioreactors can reduce nitrogen and phosphorus, prevent eutrophication and contribute to good water quality, however they have yet not been widely tested outdoors (Sarker & Kaparaju, 2023), especially for reductions of PFAS, PCBs, PAHs and metals. Only limited research has been conducted on pharmaceuticals, such as ibuprofen and diclofenac (anti-inflammatories), and carbamazepine (anticonvulsant) (García-Galán et al., 2021), and pesticides such as propanil and acetamiprid (Avila et al., 2022).

**The RHE-MEDiation project expanded knowledge on the capacity of photobioreactors to remove industrial chemicals (such as PFAS), metals, pesticides and pharmaceuticals** (Figure 2). The flexible, scalable and sustainable configuration of the RHE-MEDiation approach can support small- to medium-sized municipalities to meet UWWTD requirements, as well as current and future environmental objectives. **The system can remove biodegradable organic matter (secondary wastewater treatment), pollutants (tertiary), emerging pollutants (quaternary), or can treat surface water.** Although the effluent is not suitable for human consumption (potable), it could be used for environmental discharge and potential non-potable applications (e.g. irrigation, if the treated water conforms to the requirements of the EU Water Reuse Regulation) with additional disinfection to ensure microbiological safety. It is a nature-based, low-energy solution to support the EU Zero Pollution Action Plan[10].

[10] EC Communication COM/2021/400: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0400




Credit: RHE-MEDiation project.

**Figure 2:** The main technical components of the RHE-MEDiation system.

The remediation technology is based on the BLUEMATER[11] Green Dune® photobioreactor (Figure 3): **a treatment module that maximises growth of microalgae present in the water** by optimising the surface area to volume ratio and allowing efficient light penetration. The microalgae use natural sunlight, the nutrients in the water (nitrogen, phosphorous) and organic matter to grow. If needed, gas bubbles are injected into the photobioreactor to efficiently distribute the nutrients and $CO_2$, and prevent sedimentation at the bottom of the reactor. The pollutants present in the water are metabolised by the microalgae, stored in their cells or attached to their membranes.

**Fixed and mobile observation units and sensors are used to monitor pollutant dynamics in real time.** The fixed units, developed by MDM[12], are installed at the inlet and outlet of the photobioreactors and track changes in the water within the system. A compact, multiparametric Smart Cable Water sensor, developed by SENSICHIPS[13], is trained using machine learning to detect hazardous substances, such as heavy metals and pharmaceuticals. These advanced sensors and other built-in automated control systems monitor critical parameters (e.g. pH, temperature) in real time, allowing rapid, remote adjustments to the photobioreactors (e.g. changing flow rate) for maximum efficiency.

Two formats of the mobile marine-surface units from MDM are available:

1) Low-cost, unmotorised marine drifters (Figure 4) deployed in a predefined coastal region to collect low-frequency data that is uploaded to a cloud service; and
2) Autonomous Surface Vehicles (ASV) that perform high-frequency sampling to spatially assess pH, salinity, dissolved oxygen, and other ecological indicators of water quality.

11 https://www.bluemater.com/
12 https://www.mdmteam.eu/
13 https://www.sensichips.com/


Credit: EYDAP

**Figure 3:** Photobioreactors GREEN DUNE® installed at the Thriasio Wastewater Treatment Plant, Greece.

Both fixed and mobile units provide geo-tagged data to EMODnet[14] through an automated Data Ingestion Service developed by RINA-C[15].

RHE-MEDiation's adaptive microalgae-based technology is compact and modular, and can easily be integrated within existing infrastructure to complement other water treatment processes. The system maximises efficiency with a smaller footprint than traditional treatment methods. It can treat up to 3,000 $m^3$ of wastewater per hectare, requiring less space than activated sludge systems.

The capital outlay for RHE-MEDiation technologies is similar to reverse osmosis and traditional wastewater treatment systems. The operational costs of the RHE-MEDiation system are about half that of reverse osmosis. Energy consumption is minimal, as the system operates primarily through semi-automated, passive processes, and uses continuous gravitational wastewater flow and natural sunlight. The microalgae produce oxygen that is utilised by bacteria to decompose the residual organic substances, lowering **the need for mechanical aeration. This results in an estimated energy cost reduction of approximately 75% compared with traditional wastewater treatment technologies. Therefore, the RHE-MEDiation system reduces operational expenditure, has a much lower carbon footprint, and facilitates the treatment of urban and industrial wastewater for reuse.**

The Green Dune® photobioreactors only require chemicals for calibration, optimisation and membrane cleaning, and depending on the carbon load of the effluent, $CO_2$ may be needed to enhance microalgae growth during installation. The frequency with which photobioreactors need to be cleaned varies depending on the species of microalgae dominating the system. The **leftover sludge is mainly concentrated microalgae biomass which can be a resource for secondary products,** such as fertiliser or biofuel (mainly bioethanol and biogas). However, the classification and management of the biomass depend on the origin of the effluent to be treated and its potential reuse. For instance, preliminary results from the RHE-MEDiation system suggest that the metal accumulation in the biomass is within the limits established by the EU Sewage Sludge Directive[16] for agricultural reuse, but further research is needed. The biomass can also be incinerated (pyrolysed) to degrade or concentrate the pollutants, and to produce valuable biochar, that can be used as a filter in wastewater treatment.

## Adaptable approach to local and regional realities

**The modular nature of the RHE-MEDiation system makes it scalable and adaptable** (Figure 5). The flexible design and simple integration of this system are ideal to complement water treatment in small to medium-sized municipalities in rural or remote areas where space is not a constraint.

By changing the inlet flow and the duration of water residence, **the system can accommodate local and seasonal variations** caused by the natural and diverse microalgae community present in the wastewater or surface water. During low sunlight periods (e.g. winter), productivity declines but does not stop as some microalgae species can continue to survive on $CO_2$ and organic carbon. Artificial light can be used to compensate reduced light intensity, but this requires a thorough evaluation of the environmental conditions, nature and load of the effluent, the desired water quality to be achieved and the energy availability (e.g. via solar panels). Productivity could also be impacted temporarily by adverse weather conditions or toxic shocks (the entry of toxic substances into the system). However, the natural microalgae and bacteria in the photobioreactors will regenerate within a few days and biofilm-based microalgae provide additional community resilience. The system is also equipped with an ultrafiltration unit, that retains the microalgae and bacteria in the system.

14 https://ingestion-erddap.emodnet-physics.eu/erddap/search/index.html
15 https://www.rina.org/
16 Council Directive 86/278/EEC https://eur-lex.europa.eu/eli/dir/1986/278

The RHE-Mediation system has been tested at three demonstration sites:

- The Thriasio Wastewater Treatment Plant, operated by EYDAP[17], that serves several urban municipalities, and nearby industries and businesses, and discharges into the Gulf of Elefsis (**Attica, Greece**). Here, the RHE-MEDiation system was implemented as a post-secondary treatment, enabling the evaluation of its removal efficiency for chemical pollutants that partially or completely escape traditional treatment. After recycling 3,500 $m^3$ of wastewater, the results demonstrate effective removal (50-100%) of nutrients and metals (Zinc and Lead), achieving maximum removal efficiencies of >50% for more than 100 pharmaceutical compounds, industrial chemicals (including PFAS), artificial sweeteners, stimulants, personal care products, plant protection products, surfactants, PAHs and PCBs. The system treated Acesulfame (suspected to increase the risk of cancer) and the pharmaceuticals Triclosan and Rifaximin by 100% in all cases. It also achieved a maximum removal efficiency of 100% for Perfluorodecanoic acid (PFDA), Perfluorododecanoic acid (PFDoA), Atenolol, Caffeine, Nicotine, Fludioxonil, Trazodone, Pentachlorophenol and Clopidogrel. Furthermore, the system treated Perfluorooctanesulfonic acid (PFOS) with a maximum removal efficiency of 98% and Perfluorononanoic acid (PFNA) with a maximum removal efficiency of 78%. These removal rates were in accordance with EU and national legislation and environmental objectives.

- The Dilovası Municipal Advanced Biological Wastewater Treatment Plant, operated by YURT MUH[18], treats domestic and industrial wastewater and discharges into İzmit Bay (**Kocaeli, Türkiye**). The RHE-MEDiation system was implemented after primary treatment, testing the system with higher organic and suspended loads. After recycling 500 $m^3$ of wastewater, results show efficient removal rates for nutrients (40-97%), priority metals such as Nickel, Lead and Mercury (>50%), other pollutants, such as PAHs and pesticides (>50%), and high rates for suspended material (73-95%), meeting national discharging limits.

- The Vivaio Leggiadrezze nursery tested the system to treat natural waters from the Galeso River, degraded by illegal landfills on its shores, and discharging to Mar Piccolo (**Taranto, Italy**). The RHE-MEDiation system continuously monitored nutrients and chemical compounds and yielded average nutrient removal (>30%) and efficient removal of Boron (>20-70%).

The RHE-Mediation demonstration sites show the **removal of nutrients, metals and chemicals from wastewater and natural waters in a context-, compound- and season-dependent manner.** However, further testing and fine-tuning are required to face operational challenges such as filter clogging due to increased algae proliferation. Some variability in the results can be linked to operational fluctuations during the system installation and initial operation. Variability could also be due to the varying species of microalgae and bacteria in the treated water. As the RHE-Mediation system was tested across different environments and seasons, the findings highlight the dynamic nature of the photobioreactors, with the removal of pollutants such as phosphorus depending on the microalgae species community. The highest removal rates for the pollutants generally occurred in summer, driven by higher temperatures and radiance.

Importantly, future implementers should thoroughly assess:
1) the characteristics of the effluent to be treated;
2) the desired water quality to be achieved; and
3) the intended use of the treated water or its discharge location,

to ensure that the RHE-MEDiation system fulfil their needs.

Credit: MDM Team

**Figure 4:** Monitoring node to collect water data during a trial.

[17] https://www.eydap.gr/en/home
[18] http://yurtmuhendislik.com.tr/

The RHE-MEDiation project also developed **replication strategies and roadmaps with local authorities in Bulgaria, Egypt, Moldova and Morocco,** who benefitted from a European grant to showcase the feasibility, replicability and scale-up of the RHE-MEDiation approach to tackle pollution at their selected sites. This targeted collaboration enhanced connections between Europe and its neighbouring regions, triggering long-term collaboration in the Mediterranean region. It also offered opportunities to strengthen institutional cooperation through technical assistance, policy dialogue and shared learning mechanisms, including access to training modules, test site peer-exchange sessions, and hands-on support for adapting the remediation technologies to local environmental and regulatory conditions. Matchmaking between solution providers and regional authorities was facilitated, enabling co-designed implementation plans that reflect both scientific evidence and territorial priorities, as well as overcoming fragmentation of water management responsibilities.

However, effective implementation requires:
1) technological capacity,
2) enabling governance structures,
3) institutional readiness,
4) inter-agency coordination and
5) political commitment to long-term environmental goals.

For instance, municipalities are mostly responsible for water treatment in European countries, while different authorities, such as ministries or individual water treatment plants, might share responsibility in non-EU countries. Adaptability is key to ensuring that future replication sites tailor the intervention to their ecological, social and regulatory contexts, enhancing the long-term success and scalability of pollution remediation actions.

## Inclusive governance through local empowerment

Systematic stakeholder engagement during the RHE-MEDiation project enabled empowerment at all levels, and multiplied the endorsement, acceptance and adoption of the approach at local, regional and national levels. This was based on continuous, multi-level engagement with citizens and stakeholders, which ensured that environmental solutions were both legitimate and sustainable.


**Figure 5:** The RHE-MEDiation system installed in the Dilovası Wastewater Treatment Plant, Türkiye.

To engage with local administrations, civil society groups, industry and the youth (school and university students), surveys, direct interactions, workshops with round-table discussions, and outreach and awareness initiatives were organised. These allowed stakeholders to express their opinions on chemical pollution and to co-design the pilot actions. Site-specific validation with stakeholders enabled design optimisation and monitoring- and regulatory alignment, while building trust. Subsequent engagement activities were expanded from the local to the national level, where financial barriers and the need for better technical capacity were discussed. The discussions not only focused on the immediate benefits but also the broader social implications of the RHE-MEDiation approach.

Some possible social benefits include:
- Access to cleaner water;
- Less odour and better public health for the local community due to improved water treatment infrastructures;
- Lower pressure on potable water reserves as legally compliant, treated wastewater can be used for non-potable applications;
- Contribution to economic development by creating local employment opportunities;
- Safer working conditions due to reduced chemical use;
- Engagement with local industries and suppliers to enhance the sustainability of the sector; and
- Promotion of new technologies in the water treatment sector and for monitoring.

The RHE-MEDiation approach showed positive social impacts on the local community, while being economically advantageous in the long term.

## Recommendations

The RHE-MEDiation approach addresses existing and emerging pollutants, aligns with the EU pollution and climate goals (e.g. reducing $CO_2$ emissions of wastewater treatment plants), and allows for biomass valorisation (e.g. production of biofuel from leftover sludge), offering both environmental and economic co-benefits. Based on the project's findings and experience in testing an innovative remediation technology to destress the Mediterranean Sea from chemical pollution, the following recommendations will help to modernise wastewater treatment and enable uptake of the RHE-MEDiation approach:

### Pollution Prevention & Risk Reduction

- **The European Commission** should prioritise the reduction and phase-out of known harmful substances and enforce environmental and social (including health) impact assessments of new substances as pollution prevention measures.
- **Regional and local authorities** should promote the deployment of real-time monitoring as early-warning systems to detect water treatment plant failure, or accidental/illicit pollution from untreated hazardous/toxic compounds or substances.

### Recognition of Microalgae-Based Treatment

- **EU Member States and regional and local authorities** should recognise microalgae-based wastewater treatment systems as a secondary, tertiary, quaternary, or all-treatment option to facilitate the implementation of the UWWTD and Water Reuse Regulation, and to contribute to the objectives of the WFD and MSFD.
- **The European Commission, EU Member States, and regional and local authorities** should incentivise public-private-academic partnerships to further investigate the implementation of microalgae-based wastewater treatment in diverse sectors (e.g. agriculture; hospitals; slaughterhouses and meat processing; and textile, pharmaceutical, food and beverage industries), accelerate the adoption of innovative water treatment approaches, and explore alternative uses of the resultant water and biomass (e.g. construction, equipment refrigeration, energy generation).
- **The European Commission and EU Member States** should provide technical guidelines and financial incentives for the assessment of effluent characteristics and definition of treatment goals in rural or remote small- to medium-sized communities (more than 1,000 inhabitants), to adopt and integrate microalgae-based treatment plants into existing infrastructure, where land is available but adequate wastewater treatment infrastructure is lacking.

### Standards, Targets & Regulatory Harmonisation

- **The European Commission** should establish clear and specific pollutant removal targets and standards for accepted emission levels of emerging pollutants (e.g. pharmaceuticals, personal care products and PFAS) in EU water directives, to ensure consistency across Member States.
- **The European Commission** should harmonise EU-level standards on permissible pollutant levels for safe reuse of treated water and biomass (e.g. as fertiliser or biofuel) to promote the reuse of these products in agriculture or other industrial activities.

### Monitoring & Indicators

- **The European Commission** should develop standardised monitoring and clear technical guidance (e.g. laboratory procedures) to ensure compliance with the established pollutant emission limits, including performance indicators for $CO_2$ sequestration by microalgae and biomass reuse potential.

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# Artificial intelligence statement

Artificial Intelligence-powered tool Chat GPT has been used to assist with the language editing of this document. Artificial Intelligence has not been used for any key writing task, such as producing scientific insights, creating a literature review, drawing scientific conclusions or providing recommendations.

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